THE NEUTRINO MASS DIRECT MEASUREMENTS

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Abstract

One of the most important tasks in neutrino physics is to determine the neutrino mass scale to distinguish between hierarchical and degenerate neutrino mass models and to clarify the role of neutrinos as dark matter particles in the universe. The current tritium β decay experiments at Mainz and Troitsk are reaching their sensitivity limit. The different options for a next generation direct neutrino mass experiment with sub-eV sensitivity are discussed. The KATRIN experiment, which will investigate the tritium β spectrum with an unprecedented precision, is being prepared to reach a sensitivity of 0.2 eV.

1 Introduction

Neutrinos are about 1 billion times more abundant in the universe than baryons. Therefore already tiny neutrino masses of a few tenth eV could contribute significantly to the dark matter of the universe and influence structure formation and the evolution of the universe. Recent experimental results from atmospheric and solar neutrinos (see [1] and references therein) as well as from reactor neutrinos [2] give strong evidence that neutrinos oscillate from one flavor state into another. Therefore, a neutrino of one specific flavor eigenstate $\nu_\alpha = \sum_i U_{\alpha i} \nu_i$ is a non-trivial superposition of neutrino mass states ν_i, with at least two non-zero neutrino mass values $m(\nu_i)$. Future oscillation experiments will determine the elements $U_{\alpha i}$ with great precision.

However, ν–oscillations experiments do not yield the values of the neutrino masses. In the case of pure neutrino vacuum oscillation they are only sensitive to differences between squared neutrino masses $\Delta m_{ij}^2 = |m^2(\nu_i) - m^2(\nu_j)|$. The values Δm_{ij}^2 from

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oscillation experiments only give lower limits on neutrino masses $max\,(m(\nu_i), m(\nu_j)) \geq \sqrt{\Delta m_{ij}^2}$. On the other hand, if the absolute value of one mass eigenstate ν_i is known, all other neutrino masses can be reconstructed with the help of the differences of the squared neutrino masses (if the signs of the different $m^2(\nu_i) - m^2(\nu_j)$ values are known).

Information on neutrino masses can be inferred by astrophysical observations and by laboratory experiments, using two different approaches for the latter case: the so-called "direct mass measurements" and the search for neutrinoless double β decay. Both methods give complementary information on the neutrino masses $m(\nu_i)$ as outlined in section 3.

Except time-of-flight measurements of neutrinos emitted in a supernova the direct neutrino mass method is investigating the kinematics of weak decays. Here the charged decay products are measured and the missing neutrino mass is reconstructed from the kinematics of the charged particles by using energy and momentum conservation.

From its principle, a kinematical neutrino mass measurement yields information on the different mass eigenstates $m(\nu_i)$, but usually the different neutrino mass eigenstates cannot be resolved by the experiment. Therefore for a measurement of a neutrino flavor ν_α an average over the neutrino mass eigenstates ν_i contributing according to their mixing $U_{\alpha i}$ is obtained:

$$m^2(\nu_\alpha) = \sum_i |U_{\alpha i}^2| \cdot m^2(\nu_i) \tag{1}$$

The most sensitive information on a neutrino mass from direct mass experiments are the lowest upper limits of a few eV obtained for the mass of the electron neutrino by the investigation of the tritium β decay. The present upper limits on the mass of the muon and tau neutrinos are $m(\nu_\mu) < 190$ keV (90 % C.L.) and $m(\nu_\tau) < 18.2$ MeV (90 % C.L.) [1].

This paper is organized as follows: In section 2 the recent results of the tritium β decay experiments at Mainz and Troitsk are presented. In section 3 the motivation, the options and requirements for future neutrino mass measurements are discussed briefly. In section 4 the upcoming KArlsruhe TRItium Neutrino experiment KATRIN is presented. Section 5 gives the conclusions.

2   The Mainz and Troitsk tritium β decay experiments

The Mainz and Troitsk tritium β decay experiments are using both integrating β electron spectrometers of MAC-E-Filter type, which provide high luminosity and low background combined with an energy resolution of 4.8 eV and 3.5 eV, respectively.
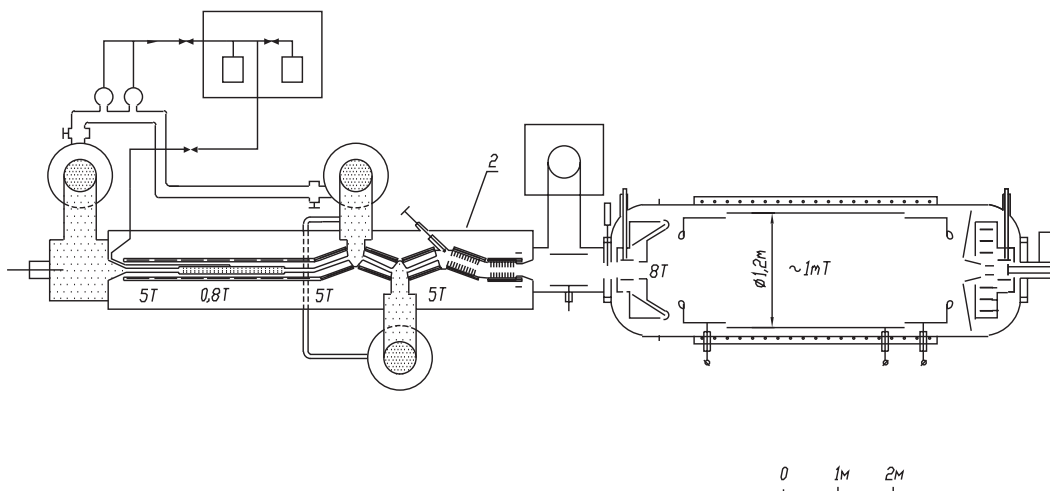
Figure 1: Schematic view of the Troitsk experimental setup [3], showing from left to right:the windowless gaseous tritium source of a 3 m long tube of 50 mm diameter, the differential and cryo-pumping section, the integrating electrostatic spectrometer of MAC-E-Filter type.

Mainz uses a thin film of molecular tritium quench-condensed on a cold graphite substrate as tritium source, whereas Troitsk has chosen a windowless gaseous molecular tritium source. After the upgrade of the Mainz experiment in 1995-1997 both experiments are running with similar signal and background rates.

2.1 The Troitsk results

Figure 1 shows the Troitsk neutrino mass experiment. From its first data taking in 1994 on the Troitsk experiment reports an anomalous excess in the experimental β spectrum appearing as a sharp step of the count rate at a few eV below the endpoint of the β spectrum E_0 [3]. Since the Troitsk spectrometer is integrating, this step corresponds to a line in the primary spectrum with a relative intensity of about 10^{-10} of the total decay rate. Later the Troitsk group reported that the position of this line oscillates with a frequency of 0.5 years between 5 eV and 15 eV below E_0 [4]. The Troitsk experiment is correcting for this anomaly by fitting an additional line to the β spectrum run-by-run.

Combining the 2001 results with the previous ones from 1994–1999 [5] gives [6]

$$m^2(\nu_e) = -2.3 \pm 2.5 \pm 2.0 \text{ eV}^2/\text{c}^4 \qquad (2)$$

from which an upper limit on $m(\nu_e)$ is obtained of

$$m(\nu_e) < 2.05 \text{ eV}/\text{c}^2 \quad (95 \text{ \% C.L.}) \qquad (3)$$

This limit is valid under the assumption that the anomalous excess count rate near the endpoint is described by an additional line correctly.

2.2 The recent Mainz data

After the upgrade at Mainz runs of a total length of about 1 year have been taken up to the end of 2001. From late 1998 on a high-frequency pulsing on one of the electrodes was applied inbetween measurements every 20 s to lower and stabilize the background. From that time on no indication of any Troitsk-like anomaly was observed. Background instabilities did not allow to extract neutrino mass results for the 2000 data.

Additional studies on quench condensed T_2 films clarified their energy loss function [7], their self-charging [8], and their dewetting as a function of temperature [9].

Fig. 2 shows the integral count rate averaged over the 1998/1999 and 2001 runs as function close to the endpoint $E_0 = 18575$ eV; data obtained in 1994 [10] are shown for comparison. The improved Mainz setup yields a signal-to-background ratio 10 times better than before and much better statistics has been obtained meanwhile.

Figure 3 shows the fit results on m_ν^2 with statistical and total uncertainties for the 4 different runs Q5 to Q8 of 1998/1999 and of Q11 and Q12 of 2001 as function of the lower energy limit of the data interval used for the analysis. The monotonous trend towards negative values of m_ν^2 for larger fit intervals as it was observed for the Mainz 1991 and 1994 data [10] has vanished. This shows that the dewetting of the T_2 film from the graphite substrate [9] indeed was the reason for this behavior. Now this effect is safely suppressed at the much lower temperature of the T_2 film. Moreover, the neutrino squared masses obtained from the fit are very stable and compatible with zero within their uncertainties and the previous Mainz results (see figure 3). No indication of a Troitsk-like anomaly or any residual problem in the Mainz data were found.

For the data set of 1998 and 1999 the energy interval of the last 70 eV below the endpoint the combined statistical and systematic uncertainty attains a minimum. The result for m_ν^2 is [11]

$$m_\nu^2 = -1.6 \pm 2.5 \pm 2.1 \text{ eV}^2/\text{c}^4 \,. \tag{4}$$

The result for the 2001 data of the last 70 eV of the β spectrum below the endpoint ($E_{\text{low}} = 18.5$ keV, see fig. 3) on $m^2(\nu_e)$ is [12]:

$$m^2(\nu_e) = +0.1 \pm 4.2 \pm 2.0 \text{ eV}^2/\text{c}^4 \tag{5}$$

Combining this value with the one obtained from the data sets from 1998 and 1999 (4) gives

$$m^2(\nu_e) = -1.2 \pm 2.2 \pm 2.1 \text{ eV}^2/\text{c}^4 \tag{6}$$

which corresponds to an upper limit [12] of

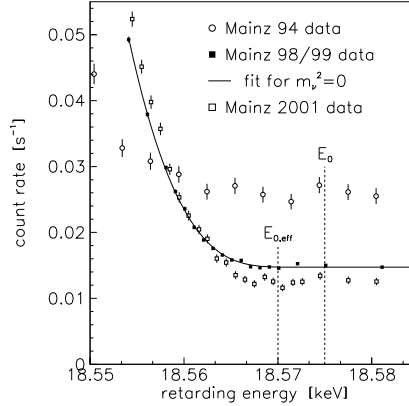$$m(\nu_e) < 2.2 \text{ eV}/\text{c}^2 \quad (95 \text{ \% C.L.}) \tag{7}$$

Figure 2: Averaged count rate of the 1998/1999 Mainz data filled squares) with fit (line) and of the 2001 Mainz data (open squares) im comparison with previous Mainz data from 1994 (open circles) [10] as function of the retarding energy $-eU$ near the endpoint E_0, and effective endpoint $E_{0,eff}$. The position of the latter takes into account the width of response function of the setup and the mean rotation-vibration excitation energy of the electronic ground state of the $^3\text{HeT}^+$ daughter molecule.

The inclusion of the high-quality data from 2001 improves the Mainz sensitivity only marginally, showing that the Mainz experiment has reached its sensitivity limit.

In spring 2002 the Mainz group has installed a new electrode system to check new ideas to avoid background and to remove trapped particles. First measurements, performed after this conference, showed that the new ideas indeed are reducing the background rate by nearly a factor of 3.

3   Future direct neutrino mass searches

The compelling evidence for non-zero neutrino masses from atmospheric, solar and reactor neutrino experiments – as briefly discussed in section 1 – provides squared neutrino mass differences but no absolute neutrino masses. This fact clearly demand for the determination of the absolute neutrino mass scale as one of the most important next steps in neutrino physics since the absolute neutrino mass has strong consequences for astrophysics and cosmology as well as for nuclear and particle physics: The neutrino mass states can be arranged in a hierarchical way like the charged fermions. This would mean that the different neutrino masses are essentially governed by the square roots of Δm_{ij}^2. On the other hand the neutrino masses could be quasi-degenerate with about the same value – *e.g.* a few tenth of an eV – and small mass differences between the different states to explain the oscillation signal. The latter case would be very important for cosmology (concerning structure formation,
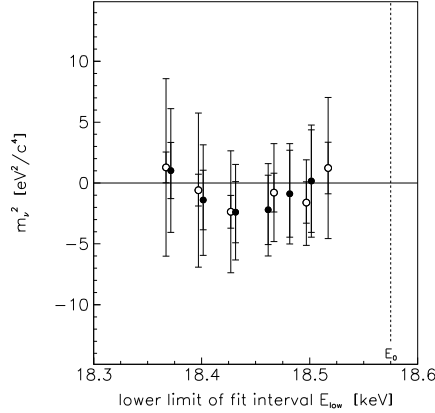
Figure 3: Mainz fit results on $m^2(\nu_e)$ as a function of the the lower boundary of the fit interval (the upper bound is fixed at 18.66 keV, well above E_0) for data from 1998 and 1999 [11] (open circles) and from the last runs of 2001 (filled circles) [12]. The error bars show the statistical uncertainties (inner bar) and the total uncertainty (outer bar). The correlation of data points for large fit intervals is due to the uncertainties of the systematic corrections, which are dominant for fit intervals with a lower boundary $E_{low} < 18.5$ keV.

evolution of the universe, ...) the former one much less. Both scenarios would require different expansions of the Standard Model of particle physics to include these neutrino masses.

The various ideas and approaches to determine the absolute neutrino mass with sub-eV sensitivity will be briefly discussed in the following:

3.1 Cosmic microwave background radiation and large scale structure

The observation of the structure in the universe at different scales and the angular distribution of the fluctuations of the cosmic microwave background radiation allows to set constraints on the Hot Dark Matter content of the early universe and because of the relic neutrino density of about 112 neutrinos per flavour and cm^3 on the neutrino mass. Although very recently the WMAP experiment [13] reports on an upper limit of the masses of all neutrino of 0.7 eV, the results derived this way is model dependent (a more conservative approach gives limits of 1 eV or 2 eV, respectively [15]). The model dependence is clearly illustrated by the fact, that Allen *et al.* obtain a non-zero sum of all neutrino masses of 0.64 eV from nearly the same data by changing some assumptions on mass fluctuations (different amplitude of mass fluctuations on $8h^{-1}$ Mpc scales σ_8) [14]. Additionally, there are strong degeneracies between the different astrophysical parameters and it is therefore very helpful to bring in information from

laboratory neutrino mass experiments to determine the other astrophysics parameters more precisely. Last but not least, one should not forget, that the present cosmological model depends on yet non-understood "Dark Energy", non-identified Cold Dark Matter and non-understood inflation, therefore, the laboratory measurement of the neutrino mass scale could serve as an important check of standard cosmology.

3.2 Time-of-flight of supernova neutrinos

Due to the smallness of neutrino masses the only laboratory to measure them by time-of-flight is our universe. The correlation between energy and arrival time on earth of supernova neutrinos depends on their mass, thus allowing to extract the neutrino mass by measuring arrival time and energy. Although a supernova, exploding within our galaxy, would give hundreds to thousands of neutrino events in the current underground neutrino detectors, the systematic uncertainty connected with the not precisely known neutrino emission time spectrum does not allow a sub-eV sensitivity on the neutrino mass.

3.3 Neutrinoless double β decay

The neutrinoless double β decay is sensitive to the so-called "effective" neutrino mass

$$m_{ee} = |\sum_i U_{ei}^2 \cdot m(\nu_i)| \quad , \tag{8}$$

which is a coherent sum over all mass eigenstates contributing to the electron neutrino. The determination of m_{ee} from the measurement of the neutrinoless double β decay rate is complementary to the direct determination of the mass of the electron neutrino since m_{ee} and $m(\nu_e)$ can differ by the following reasons:

1. Double β decay requires the neutrino to be a Majorana particle.

2. In the notation of eq. (8) the values U_{ei}^2 can have – in addition to a possible complex phase from the 3×3 neutrino mixing – two non-trivial so-called Majorana phases. This could lead to a partial cancellation of the different terms of the sum. Especially that the recent solar neutrino data point to large mixing opens this possibility [16].

3. The uncertainty of the nuclear matrix elements of neutrinoless double β decay still contributes to the uncertainty of m_{ee} by about a factor of 2 .

4. Non Standard Model processes, others than the exchange of a Majorana neutrino, could enhance the observed neutrinoless double β decay rate without changing m_{ee}.

The proposed double β decay experiments of the next generation aim for a sensitivity on m_{ee} in the range of 0.1 eV and below [17].

3.4 Rhenium cryogenic bolometer experiments

A straightforward approach to directly measure the electron neutrino mass is the use of cryogenic bolometers. This new technique has been applied to the isotope ^{187}Re, which has with $E_0 = 2.5$ keV the lowest β endpoint energy and which optimizes the interesting fraction below the endpoint [18, 19]. The experiments are still in the early stage of development. Current Rhenium micro-calorimeters reach an energy resolution of $\Delta E \sim 30$ eV [18] and yield an upper limits of 22 eV and 26 eV, respectively [18, 19]. To further improve the statistical accuracy the operation of large arrays of micro-calorimeters with better resolution is required. New techniques are explored to enable these improvements. The expected sensitivity on $m(\nu_e)$ in the future is in the eV region [19].

3.5 The KATRIN experiment

Summarizing the discussion above clearly means that one or more next generation double β decay experiments have to be performed due to their very low sensitivity. But considering the complementariness of neutrinoless double β decay and the direct neutrino mass determination it is also clear that a next generation direct mass search has to be done. None of the alternative direct methods discussed above is able to provide a sub-eV sensitivity in a model independent way within the next decade. Therefore, it is straightforward to explore which sensitivity could be achieved by investigating the tritium β decay spectrum near its endpoint with the very successful MAC-E-Filter as spectrometer.

Discussions between groups from Mainz, Karlsruhe and Troitsk led to the proposal for a next generation tritium β decay experiment to be built at Forschungszentrum Karlsruhe/Germany. Now a strong collaboration including nearly the complete worldwide expertise on tritium β decay neutrino mass experiments has come together and has published a Letter of Intent for the KATRIN experiment (KArlsruhe TRItium Neutrino experiment) [20].

4 The KATRIN experiment

The KATRIN collaboration has enlarged and improved the proposed setup compared to its Letter of Intent [20]. Figure 4) shows a schematic view of the proposed experimental configuration. The windowless gaseous tritium source (WGTS) allows the measurement of the endpoint region of the tritium β decay and consequently the determination of the neutrino mass with a minimum of systematic uncertainties from the tritium source. The WGTS will consist of a 10 m long cylindrical tube of 90 mm diameter filled from the middle with T_2 gas, resulting in a source column density of about $(\rho d) \approx 5 \cdot 10^{17}$ molecules/cm^2. With these values the count rate is increased
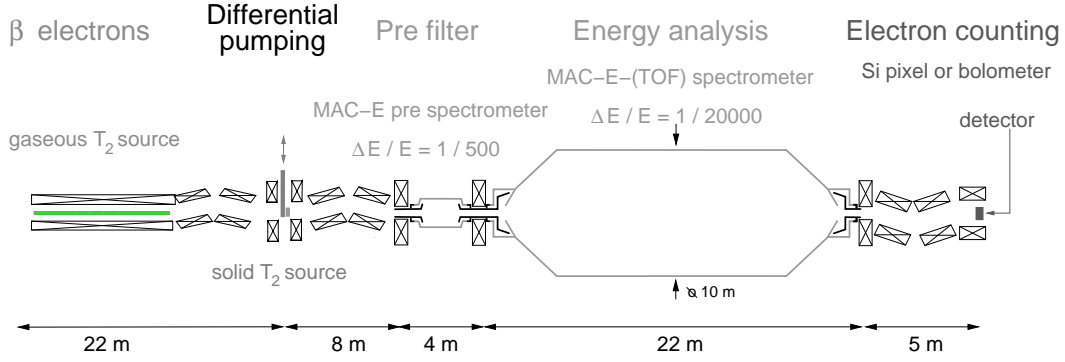
Figure 4: Schematic view of the proposed next-generation tritium β decay experiment KATRIN. The main components of the system comprise a windowless gaseous tritium source (WGTS), a alternative quench condensed tritium source (QCTS), a pre-spectrometer, a large electrostatic spectrometer with an energy resolution of $1\,\mathrm{eV}$ and a detector. An electron transport system guides electrons from the T_2 sources to the spectrometers, while eliminating all tritium molecules.

by two orders of magnitude with respect to the Troitsk experiment. A quench condensed tritium source (QCTS) following the source concept of the Mainz experiment is considered as a second alternative source, which has complementary systematics.

The electron transport system adiabatically guides β decay electrons from the tritium sources to the spectrometer while at the same time eliminating any tritium flow towards the spectrometer, which has to be kept practically free of tritium for background reasons. The first part of the transport system consists of a differential pumping section with a tritium reduction of a factor 10^9, the second part of a liquid helium cold cryo-trapping section.

Between the tritium sources and the main spectrometer a pre-spectrometer of MAC-E-Filter type will be inserted, acting as an energy pre-filter to reject all β electrons except the ones in the region of interest close to the endpoint E_0. This minimizes the chances of causing background by ionization of residual gas in the main spectrometer. As the designs of the pre- and main spectrometer will be similar, the former is acting as a test facility for the larger main spectrometer. The design and construction of the pre-spectrometer has already started.

A key component of the new experiment will be the large electrostatic main spectrometer with a diameter of $10\,\mathrm{m}$ and an overall length of about $22\,\mathrm{m}$. This high resolution MAC-E-Filter will allow to scan the tritium β decay endpoint with increased luminosity at a resolution of a little bit less than $1\,\mathrm{eV}$, which is a factor of 4 better than present MAC-E-Filters at Mainz and Troitsk. The 200 times larger analyzing plane with respect to the Mainz experiment allows the remaining factor 50 to be utilized to increase the source cross section and, correspondingly, the signal rate.

The detector requires high efficiency for electrons at $E_0 = 18.6$ keV and low γ background. A high energy resolution of $\Delta E < 600\,\mathrm{eV}$ for $18.6\,\mathrm{keV}$ electrons should suppress background events at different energies. The present concept of the detector is based on a large array of about 1000 silicon drift detectors surrounded by low-level passive shielding and an active veto counter to reduce background.

At the International Workshop on Neutrino Telescopes already the proposed enlarged version of the KATRIN experiment comprising a WGTS with 90 mm diameter and a main spectrometer with 10 m diameter was presented and consequently a sensitivity of 0.25 eV was reported. The very recent simulations for 3 years of data taking using a new strategy of optimized measurement point distribution and improved systematics result in a neutrino mass sensitivity of even below 0.2 eV, with statistical and systematic uncertainties contributing about equally. This sensitivity number corresponds to an upper limit on the neutrino mass with 90 % C.L., if no neutrino mass would be seen. To the contrary, a non-zero neutrino mass of 0.35 eV would be detected with 5 σ significance. This sensitivity improves the existing limits by one order of magnitude and also demonstrates the discovery potential of KATRIN for an electron neutrino mass of a few tenth of an eV.

5   Summary

The current tritium β decay experiments at Mainz and Troitsk are reaching their sensitivity limits. The recent Mainz data have strictly the shape of a β spectrum with zero neutrino mass, resulting in an upper limit on $m(\nu_\mathrm{e})$ of 2.2 eV at 95 % C.L.

A laboratory neutrino mass determination with sub-eV sensitivity is clearly needed to distinguish between hierarchical and degenerate neutrino mass models and to check the role of neutrinos in the early universe. The search for the neutrinoless double β decay is one very important approach. Complementary and equally important is a next generation direct neutrino mass experiment. Discussing the different options shows that this experiment has to be a large tritium β decay experiment using a MAC-E-Filter. Such an experiment is being prepared by the KATRIN collaboration aiming for an sensitivity on the neutrino mass of below 0.2 eV.

6   Acknowledgments

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